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by

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ABSTRACT This article discusses questions associated with laser radiation transmission between the atmosphere and sea water. It introduces in detail sea water surface reflection characteristics and laser attenuation in sea water. Finally, it estimates, in accordance with typical parameters associated with current levels, airborne laser sounding capabilities.

I. INTRODUCTION

In recent years, due to swift and intense development of such technologies as satellite remote sensing, oceanic sounding, as well as sea-air communications, and so on, research associated with the optical properties of sea water grows more lively by the day. However, because sea water is intricate and complicated, applying measurement work to it is extremely difficult. Although research activities associated with the optical properties of sea water had already begun as early as 1885, progress, however, was very slight. It was only in the 1930's that there was then considerable success. What is regretable is that, in the 30 years afterward, progress in oceanic optics was still not satisfactory. After entering the 1970's, new technologies and new instruments emerged in large numbers, giving, to the greatest extent, impetus to great strides in new directions in oceanic optics.

Topics involved with the optical properties of sea water are relatively numerous. This article is limited to only discussing transmission problems associated with laser radiation between the atmosphere and sea water. It is primarily concerned with reflective properties associated with the surface of sea water and the attenuation properties of sea water on radiation in order to facilitate design and application of oceanic optics engineering to provide valuable data.

II. SEA WATER SURFACE REFLECTIVITY

When laser beams from the atmosphere pass through the surface of the sea and are incident into ocean water, at locations on the boundary surface between the air and sea water, complicated reflection and refraction processes are produced. When laser light is reflected back from targets under the water and returns to the atmosphere, similar processes are also produced in the same way. Reflection and refraction associated with boundary surface locations will make amounts of energy on predetermined light paths experience some losses. Looking from the view point of practical uses, the level of losses can be measured using reflectivity ρ. There is a close relationship between numerical values of ρ and the state of the sea surface. In cases where winds are flat and waves are quiet, the sea surface can be seen as a "mirror". However, in general cases, the ocean surface always has white caps and foam on it. As a result, overall reflection rates will include the three portions--foam reflectivity ρf , mirror reflectivity ρm, and reflectivity of light under the water ρ, that is, [1]

(1)

In the equation, W is the ratio of surface area occupied by white caps. As a result, the ratio they occupy on calm sea surfaces is (1-W). The mirror reflection portion must use (1-W)

for
weighting. The weighting factor ($1-\rho f$) used in association with the third term considers white cap reflection and reduces light under the water.

Overall foam reflectivity is a sum of all the single white cap reflectivities, that is, also

(2)

In the equation, ρe is the effective reflectivity associated with white caps. White cap surface area and wind speed are related. At the present time, there are already quite a few empirical formulae for calculating white cap surface area. Among these, the one with the best results is [2]

(3)

In this, V is wind velocity figured in m/s. The equation above is appropriate for use in situations where water temperature is higher than 14°C.

In the spectral zone of visible light, there is no
relationship between effective white cap reflectivity and wave length. However, following along with wind velocity magnitudes, there are slight differences. Generally, one adopts $\rho e = 22\%$. Table 1 is some data associated with reflectivities of relevant sea surfaces as calculated on the basis of equation (2) and equation (3). These data are in good agreement with certain measured results.

Table 1 Sea Water Surface Reflection Properties

V(m/s)	W(%)	ρ_e(%)	ρ_f(%)
4	0.00	22.0	0.01
5	0.09	22.0	0.02
6	0.16	22.0	0.04
7	0.28	22.0	0.06
8	0.45	22.0	0.10
9	0.67	22.0	0.15
10	0.98	21.7	0.15
11	1.37	21.5	0.29
12	1.86	21.4	0.40
13	2.46	21.3	0.52
14	3.19	21.2	0.68
15	4.07	21.1	0.86
16	5.11	21.0	1.07
17	6.32	20.9	1.32
18	7.73	20.8	1.61
19	9.35	20.8	1.95
20	11.2	20.7	2.32
25	24.6	20.6	5.06

Mirror reflectivities ρm can be calculated from smooth surface reflection laws (Fresnel's Law) and are a function of beam incidence angles and sea water indices of refraction. If incident light is polarized, reflected light is also capable of changing polarization properties. Table 2 is the results for calculations done on the basis of Fresnel equations. In this, ρ1 and ρ2 are, respectively, reflectivities parallel to and perpendicular to reflection surfaces. ρm is a reflectivity associated with nonpolarized light.

Table 2 Reflectivities Associated with Flat and Calm Sea Surfaces (%)

(1)入射角	ρ_1	ρ_2	ρ_m
0	2.0	2.0	2.0
5	2.0	2.1	2.0
10	1.9	2.1	2.0
15	1.8	2.3	2.0
20	1.7	2.5	2.1
25	1.4	2.7	2.1
30	1.2	3.1	2.1
35	0.9	3.6	2.3
40	0.6	4.3	2.4
45	0.3	5.3	2.8
50	0.1	6.7	3.4
55	0.2	8.6	4.4
60	0.4	11.5	5.9
65	1.7	15.8	8.7
70	4.7	21.9	13.3
75	11.0	31.3	21.2
80	24.0	45.9	34.9
85	49.3	67.4	58.3
90	100	100	100

Key: (1) Angle of Incidence

Reflectivities associated with underwater light ρu are /3
generally much smaller than the two terms discussed above. In particular, when wave lengths are placed in non window zones, it is possible to ignore them in calculations.

The reflection properties discussed above have already been

empirically verified by Bufton and others [4] with experimental measurements making use of airborne lasers (YAG multiple frequency, λ = 532nm).

III. SEA WATER ATTENUATION OF RADIATION

Table 3 Optical Properties of Pure Water (T=20°C, p=105 Pa)

λ(nm)	n	$k\times10^{10}$	$\alpha\times10^{3}\,m^{-1}$	$\beta\times10^{3}\,m^{-1}$	$\mu\times10^{3}\,m^{-1}$	$\Lambda=\beta/\mu$
250	1.337	37.8	190	32.0	220	0.15
300	1.359	9.55	40	15.0	55	0.27
320	1.354	5.09	20	12.0	32	0.38
350	1.349	3.34	12	8.2	20	0.41
400	1.343	1.91	6	4.8	11	0.44
420	1.342	1.67	5	4.0	9	0.54
440	1.340	1.40	4	3.2	7	0.46
460	1.339	0.732	2	2.7	5	0.54
480	1.337	1.15	3	2.2	5	0.44
500	1.336	2.39	6	1.9	8	0.24
520	1.336	5.79	11	1.6	16	0.10
530	1.335	9.28	22	1.5	23	0.065
540	1.335	12.5	29	1.4	30	0.047
550	1.334	15.3	35	1.3	36	0.036
560	1.334	17.4	39	1.2	40	0.030
580	1.333	34.2	74	1.1	75	0.015
600	1.333	95.5	200	0.93	200	0.0046
620	1.332	118	240	0.82	240	0.0034
640	1.332	138	270	0.72	270	0.0027
660	1.331	163	310	0.64	310	0.0021
680	1.331	206	380	0.56	380	0.0015
700	1.330	334	600	0.50	600	0.0008
740	1.329	1320	2250	0.40	2250	0.0002
750	1.329	1560	2620	0.39	2620	0.0001
760	1.329	1550	2560	0.35	2560	0.0001
800	1.328	1290	2020	0.29	2020	0.0001

The attenuation properties of sea water on radiation and the soluble and suspended materials contained in it are strongly related. Moreover, the shapes of particles dispersed in sea water are very irregular. Their dimensional distribution is also

within a very broad range. If one says the atmosphere is primarily dispersion media (With regard to visible light, this is certainly the case.), then scattering and absorption in water are both very important. Particularly in the blue green window, among all the factors that create radiation attenuation, /4 scattering processes occupy an important place. Table 3 gives some optical properties of pure water [5]. In it, n and k are, respectively, the real and imaginary parts of indices of refraction. α is absorption coefficients. β is dispersion coefficients. μ is attenuation coefficients. Λ is photon survival probabilities. From Table 3, it is possible to know that, within the 350nm - 480nm range, scattering effects and absorption effects are equivalent. At wave lengths even longer than this region, due to pure water molecule dispersion obeying the Ruili (phonetic) Law ($\beta \infty \lambda$-4) and abruptly decreasing, attenuation is primarily determined by absorption effects.

Fig.1 Relationships of Attenuation Coefficients and Wave Lengths Associated with Different Components in Sea Water

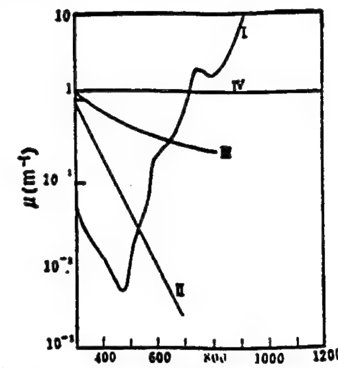


Fig.2 Optical Absorption Spectra After Mixing of Pure Water and Pigment

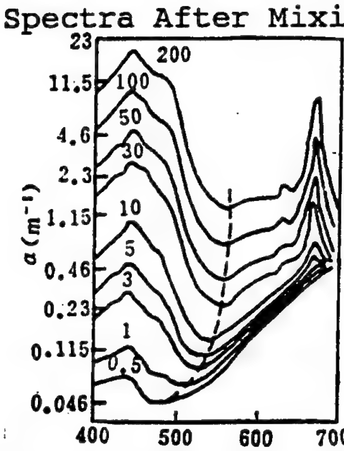
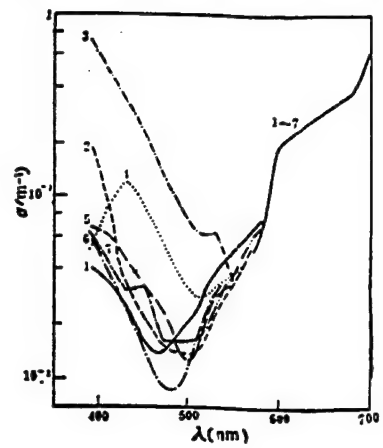


Table 3 Absorption Coefficient Optical Spectra Distribution in Different Water Regions



Key: 1-Sagasuo (phonetic) Sea 2-Caribbean Sea 3-Baerdi (phonetic) Sea Getelan (phonetic) Trench 4-Pacific Galaipangesi (phonetic) Archipelago, Depth 20m 5-Same as 4 6-Tonga Trench 7-Indian Ocean Trade Wind Ocean Current

In actual sea water, due to differences in constituent materials contained and concentrations, differences in attenuation processes are quite large. However, they roughly have the relationships between attenuation coefficients and wave lengths shown in Fig.1 [5]. Curve I is the optical attenuation spectrum for pure water. Minimum values lie in the blue area. The reason for the blue color that sea water presents lies precisely in this. Curve II is the optical absorption spectrum associated with soluble organics. In the blue zone to ultraviolet, absorption coefficients follow wave length shortening and abruptly increase. Curves III and IV are small particle (primarily minerals) and large particle optical attenuation spectra. In the Fig.'s, vertical coordinates are only in effect with respect to Curve I. The absolute values of the remaining three curves depend on their various concentrations. Fig.2 is absorption spectra after mixing of pure water and different concentrations of pigment. Numbers on the curves are indications of chlorophyll concentrations (mg/m3). We can see that locations of minimum absorption coefficient values (as shown by the broken line in the Fig.) follow along with increases in chlorophyll concentrations and shift in the long wave direction. This clearly shows that sea water window locations strongly depend on the physical properties of sea water.

The physical properties of sea water have large regional differences. This leads to sea water associated with different regions of the oceans possessing extremely large differences in optical qualities. Fig.3 brings together measurement results for seven locations. From the Fig. in question, it is possible to roughly draw the conclusions below. Absorption in the sea water of the open ocean is the smallest. Absorption in bays or gulfs is relatively large. Window locations follow along with increases in the purity levels of sea water and shift toward relatively short wave length locations. Large amounts of measurement data clearly show that, generally speaking, clear ocean water windows are at 480nm. Windows associated with /5

coastal waters of the oceans are 520-550nm. Typical attenuation coefficients are, respectively, 0.05m-1 and 0.2m-1 - 0.4m-1. In comparison to this, windows associated with pure water are 450nm. Attenuation coefficients are, approximately, 0.02m-1. However, it should be pointed out that, due to differences in levels of purity and measurement methods, attenuation coefficient measurement values have very large dispersions, roughly distributed between 0.01m-1 - 0.04m-1.

Sea water attenuations are also related to their depths. Table 4 is measurement results at seven depths in the tongue of the sea around the Bahamas archipelago [6]. It is possible to see that, below 200m depths, there are already no large differences in attenuation coefficients. Obviously, this clearly shows that, below this depth, water qualities tend toward a uniformity. In conjunction with this, attenuations for pure water have already been approached. Besides this, we are also able to discover that, at 20m depths, attenuation coefficients show the appearance of maximum values. This is related to the discovery, in investigations of the oceans, of the fact that relatively more numerous suspension particles are concentrated around depths of 20m.

Table 4 Attenuation Coefficients at Different Depths

(1) 喇[illegible]激光片号	98	45	61	21	25
(2) 峰值波长(nm)	450	495	530	580	611
(3) 半宽度(nm)	51	52	95	47	33
(4) 深度	(5) 衰减系数 (m^{-1})				
5	0.105	0.111	0.145	0.235	0.355
10	0.105	0.113	0.148	0.235	0.355
20	0.111	0.116	0.150	0.236	0.355
50	0.116	0.111	0.140	0.234	0.350
100	0.083	0.078	0.112	0.202	0.320
200	0.061	0.052	0.089	0.180	0.301
400	0.059	0.051	0.089	0.180	0.301

Key: (1) Lateng (phonetic illegible) Laser Plate No. (2) Peak Value Wave Length (3) Half Width (4) Depth (5) Attenuation Coefficients

Finally, it should be strongly pointed out that, due to the fact that differences in properties of sea water at various locations are very great, obviously, the optical properties will also follow along and be different. When we carry out various types of applications, it is very necessary that we first grasp detailed data associated with optical properties in that region of the ocean.

IV. ESTIMATES ASSOCIATED WITH AIRBORNE LASER SOUNDING CAPABILITIES

On the basis of the discussions above, we are now capable of making an estimate of the potential associated with airborne laser sounding technologies. Assuming one opts for the use of transmission equations with the form below [8]:

(4)

and, in conjunction with that, parameters are adopted as follows: transmission power PT = 107W, receiver optical spectrum penetration rate k(λ)=0.8, transmission beam and received visual field superposition coefficient k(La(unclear)) = 0.8, receiving optical system surface area Ao = 0.314m2 (D=0.2m), aircraft altitude La(unclear) = 500m, water surface reflectivity ρw(λ) = 0.1, sea bottom or underwater target reflectivity ρ(λ) = 0.1, atmospheric attenuation coefficient μa = 0.2km-1, (corresponding to a clear day with 20km visibility), then receiving power

(5)

Fig.4 Relationships Between Receiving Power and Measurement Depth (Broken Lines Are Minimum Receiving Powers Required When Discovery Probabilities Reach 60%)

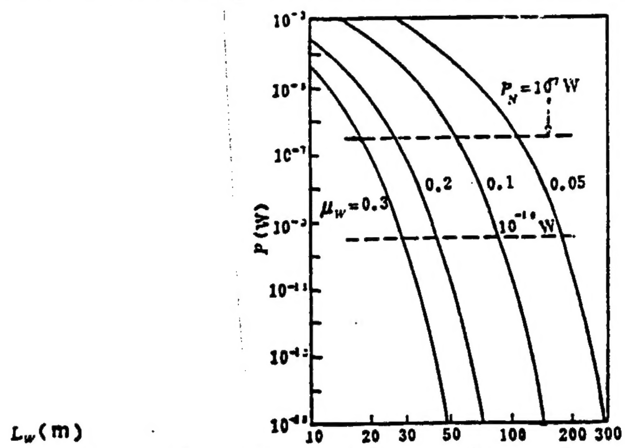


Fig. 4 is results of calculations done in accordance with equations above. From this, it is possible to know the depth of water which can be measured with severe attenuation limitations.

If option is made for the use of effective filters because of extreme background noise and depending on photoelectric multiplier tubes or other photoelectric detector noise, as well as, in conjunction with that, using signal to noise ratios of 3.1 to act as relatively reliable criteria to discover targets (at this time, discovery probability is 60%), then, when noise powers PN = 10-7W and 10-10W, with regard to the near ocean (μw ≈ 0.2m-1), it is possible to measure 27m and 44m. Moreover, with regard to the open ocean (μw = 0.05m-1), those are, respectively, 106m and 178m. Giving consideration to the fact that parameters already chosen are at a very high level, 10-10 W noise effective power is already quite a high index. Moreover, sea water with μw = 0.05m-1 is already equivalent to clear water. Therefore, as far as targets where it is hoped to measure depths exceeding 200m to even 300m and below, a lot of arduous efforts should doubtless be done and only then will it be possible to reach them.

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